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1 Title: **CONTROLLED DIFFRACTION EFFICIENCY FAR FIELD VIEWING**
2 **DEVICES**

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5 **CROSS REFERENCE TO RELATED APPLICATIONS**

6 This application claims priority under 35 U.S.C. § 119(e) from U.S. provisional
7 application no. 60/156,406, filed September 28, 1999. The 60/156,406 application is
8 incorporated herein by reference in its entirety for all purposes.

9 **BACKGROUND OF THE INVENTION**

10 **1. Field of the Invention**

11 This invention relates to controlling the brightness of light patterns created by a
12 hologram. More specifically, this invention balances the brightness of a far field
13 holographic light pattern and the clarity of a scene when viewed through a far field
14 viewing device.

15 **2. Background Information**

16 Holograms of many different types have become commonplace in modern society.
17 They are used as ornaments and as novelty items, as well as security devices on credit
18 cards. A hologram is a pattern recorded on a substrate that provides a predetermined light
19 diffraction effect.

20 There are many different types of holograms that are differentiated from one
21 another by their optical properties and behavior. Most of the commonly seen holograms
22 depend upon reflection of light from the hologram to the observer's eye. Less commonly
23 seen are transmission type holograms wherein light passes through the hologram.

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1 When an observer looks through a far field hologram at a scene that contains
2 compact bright points of light, the observer sees holographic diffracted light patterns
3 associated with each bright point location. We define this unique form of display
4 holography as a far field viewing application. Far field viewing devices are made up of
5 physical apertures (or frames) and far field holograms combined in a way designed for
6 viewing a scene and superimposing holographic light patterns around each compact bright
7 point of light in the scene.

8 Referring to **Fig. 1**, a far field viewing device containing of a far field hologram 10
9 mounted in a frame 12 is illustrated. The far field viewing device is placed in front of an
10 observer's eye 14. The observer's eye 14 looks through far field hologram 10 mounted in
11 frame 12 at a scene containing at least one bright compact source of light 16. Each point
12 in the scene is viewed through a utilized hologram area 18. Schematic depictions of a tree
13 and a star represent scene elements 20 that the observer wants to see in sharp focus.

14 Examples of far field viewing devices include the eyeglass device containing far
15 field holograms as described in U.S. Patent no. 5,546,198, as well as far field holograms
16 mounted in windows. Ordinarily, a human observer looks through a far field device.
17 Additionally, far field devices can also be incorporated into film-based or electronic image
18 capture devices, such as still or motion cameras.

19 An example of an algorithm for calculating computer generated holograms is
20 described by Gallagher and Liu. See N.C. Gallagher and B. Liu, "Method for Computing
21 Kinoforms That Reduces Image Reconstruction Error" Applied Optics, v. 12, pp.2328-
22 2335 (1973). The output of the algorithm is a set of numerical values. Each value
23 corresponds to the desired complex transmittance at a different spatial location on the
24 physical hologram. The resultant data set is used to drive any of a variety of fabrication

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1 methods which impose the desired transmittance values onto a physical substrate. There
2 are a number of methods for producing a physical computer generated hologram from a
3 set of data. These are summarized in the textbook MICROOPTICS [editor Hans P. Herzig,
4 published by Taylor and Francis, London 1997] in chapters 4 and 5. An original hologram
5 can be used as a master and copied or replicated using a variety of techniques as discussed
6 in chapter 7 of Herzig's MICROOPTICS.

7 Referring to Fig. 2, an idealized view of the overall scene as seen through an ideal
8 far field viewing device is illustrated. The ideal view contains a well-focused
9 representation of scene elements 220 in addition to a desired diffracted light pattern 222
10 produced by light diffracted by the far field hologram adjacent a bright compact source of
11 light 216. In the example, the hologram has been tailored to diffract the light pattern in the
12 form of letters spelling the word "NOEL". Fig. 2 shows only one bright compact point of
13 light to keep the illustration simple. In the case where many such sources of light are
14 present, the desired diffraction pattern will surround each bright compact source of light.

15 A salient aspect of far field viewing applications that is different from most display
16 hologram applications is that the observer is encouraged not to focus all of the attention on
17 the holographic diffracted light pattern. Instead, the observer focuses on an overall scene
18 in a unique combination with the holographic diffracted light patterns at each bright point
19 source of light present in the scene. Accordingly, it is important for the viewing device to
20 present a clear image of the scene while also presenting bright holographic light patterns.

21 It is also desirable for a far field viewing device to have a loose tolerance for the
22 distance between the observer's eye and the hologram so that the viewer is not forced to
23 maintain a particular position relative to the far field viewing device.

Additionally, it is desirable for the hologram in a far field viewing application to be capable of producing relatively large diffracted light patterns containing fine spatial detail.

The problem of balancing the clarity of the scene and the brightness of the holographic light patterns is not common in display holography. In most applications of display holography, the hologram is designed to diffract as much of the light as possible to create the brightest possible holographic reconstruction. Such a hologram is said to have high diffraction efficiency. The push in the industry is directed to design methods and fabrication processes that maximize the diffraction efficiency of display holograms since most applications of display holography call for maximum brightness in the holographic reconstruction.

Referring to **Fig. 3**, a view through a high diffraction efficiency far field hologram is illustrated. The scene elements appear as blurred images **324** when viewed through a far field transmission hologram having a high diffraction efficiency. **Fig. 3** also shows that such a far field hologram also produces an undesired diffracted light pattern **326**, symmetrically disposed about a bright compact light source **316** in the form of a mirror image of desired diffracted light pattern **322**.

In contrast, our goal for far field viewing applications is to attain a diffraction efficiency that is often considerably less than the diffraction efficiency produced by standard methods for designing and fabricating holograms. When a highly efficient far field hologram is used in a far field viewing application, the diffracted light patterns are bright but the scene appears blurred. This effect on the view of the scene is much like looking through a light diffusing piece of shower glass, and it is undesirable since viewing, not obscuration, is desired. On the other hand, when the hologram has low diffraction efficiency the scene observed through the hologram appears well focused, but

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1 the holographic light patterns surrounding the point sources of light in the scene are not
2 sufficiently bright.

3 Whereas the prior art provides no way to simultaneously maximize the scene
4 clarity and the brightness of the holographic light patterns, we recognize that the
5 diffraction efficiency of the hologram should be chosen to strike an optimum balance
6 between the un-diffracted energy and the energy in the desired diffracted light pattern.
7 The optimum diffraction efficiency can depend on the nature of the desired holographic
8 pattern as well as the expected scene characteristics. Thus, flexible and simple control in
9 achieving the desired diffraction efficiency of the hologram is needed.

10 One broad approach to the problem of reducing diffraction efficiency would be to
11 start with an established method that produces high diffraction efficiency and to modify
12 the approach to obtain reduced diffraction efficiency. The need for intentionally reducing
13 diffraction efficiency of a far field hologram in a controlled manner has not been
14 recognized in the prior art. In contrast, we have made it a goal to increase the amount of
15 un-diffracted light by reducing the amount of energy in the desired diffracted light pattern.
16 Preferably, the modified process should not substantially increase the energy into
17 undesired diffracted distributions that would distract from the desired diffracted pattern.

18 An unsatisfactory solution would be to modify standard hologram fabrication
19 processes by adjusting process parameters to achieve the desired diffraction efficiency. In
20 an amplitude hologram, it is possible to reduce the diffraction efficiency by reducing the
21 transmittance contrast of the hologram. The transmittance contrast is a measure of the
22 ratio of the highest transmittance to the lowest transmittance. Lowering the transmission
23 contrast would in fact make the diffracted pattern weaker and improve the see-through
24 performance of the hologram as desired. A significant drawback is that nonstandard

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1 processes would have to be developed to accomplish this. The use of nonstandard
2 processes leads to increased costs and increased process variations.

3 In a binary phase hologram, it is possible to reduce the diffraction efficiency by
4 changing the phase modulation depth. The phase modulation depth is a measure of the
5 maximum optical path length difference between the two transmittance states in the
6 hologram. As in the amplitude case, implementation of this solution would require
7 processes that need tight control over transmittance contrast or phase modulation depth.
8 Such processes are difficult to establish and maintain. These problems lead to increased
9 costs and questionable repeatability, since non-standard fabrication procedures would be
10 needed.

11 Additionally, a significant limitation of amplitude holograms and binary phase
12 holograms is their restriction to Hermitian symmetric holographic light reconstruction
13 patterns. Hermitian symmetry means that the desired reconstruction pattern is always
14 accompanied by a copy of the pattern that is rotated by 180 degrees about the un-diffracted
15 component. This undesired symmetric diffraction pattern in the form of a mirror image of
16 the desired pattern is distracting in many cases. Furthermore, the undesired diffraction
17 pattern takes up a large space that could otherwise be used to create larger and more
18 complicated desired diffracted light patterns.

19 As discussed in our previous patent, U.S.P. 5,546,198, multilevel phase computer
20 generated holograms (CGH's) can diffract light into asymmetric light patterns thus
21 eliminating the distracting reversed diffracted copy and enabling a larger area for more
22 complicated light patterns. In practice, such holograms are highly efficient and have poor
23 see-through performance resulting in a severely blurred scene when used in a far field
24 viewing device. The idea of decreasing diffraction efficiency by modifying process

1 parameters is not an available option for multilevel phase CGH's. Unlike the case of
2 binary CGH's, intentionally reducing the phase modulation to reduce diffraction efficiency
3 of a multilevel CGH has serious undesirable consequences. As the phase modulation
4 depth decreases, the diffraction efficiency does decrease but an additional diffracted
5 pattern appears in the form of a reversed copy of the desired pattern. In practice, the
6 strength of this reversed copy eliminates the advantage of multilevel phase holograms.

7 Referring to **Fig. 4**, a view of the scene through a multilevel phase CGH far field
8 transmission hologram is illustrated. In this view, an undesired symmetric diffraction
9 pattern has been eliminated so that only a desired diffraction pattern **422** is seen adjacent a
10 bright compact light source **416**. Elements of the natural scene are blurred as represented
11 by blurred images **424**.

12 Thus, an alternative form of the multilevel phase CGH is needed to balance see-
13 through performance with the desired holographic reconstruction without introducing
14 additional undesired diffracted light.

15 U.S. Patent no. 5,210,625 and U.S. Patent no. 5,278,008 disclose a multi-step
16 process for modifying the diffraction efficiency of optically generated holograms without
17 adjusting the contrast transmittance or the phase modulation depth over the whole
18 hologram area. The disclosures of these patents are directed to beam splitting and
19 redirecting holograms. They are silent regarding far field holograms, as well as
20 information bearing holograms.

21 The process disclosed by the '625 and '008 Patents is not applicable to far field
22 viewing devices. The disclosed aspect of introducing an unresolvable pattern of clear
23 regions may be workable for image plane and Fresnel holograms when attention is focused
24 at or near the plane of the hologram and may be useful for some beam redirection

1 applications for which it is taught. However, the '625 and '008 disclosures do not
2 recognize that the apertures defining the clear regions contribute to undesired diffracted
3 light as well as un-diffracted light. The practical result is that the teachings of the '625
4 and '008 Patents cannot be applied to far field viewing applications because the small size
5 of the unresolvable regions produces undesirable diffraction artifacts that compete with the
6 desired reconstructions of far field holograms when bright compact sources of light are
7 present in the scene.

8 Furthermore, the process of introducing unresolvable flat regions as the '625 and
9 '008 Patents can introduce undesirable degradation in the see-through performance of
10 holograms creating a blurred scene. The prior art concept of resolving the flat regions
11 really loses meaning for holograms that are situated near the pupil of the eye as in the case
12 of many far field viewing devices. Thus, different considerations are needed.

13 Moreover, the multi-step process disclosed by the '625 and '008 Patents is
14 cumbersome and is not appropriate for computer generated holography.

15 What would be useful would be far field viewing devices incorporating holograms
16 with diffraction efficiency adjusted to provide robust control over the balance between the
17 clarity of the scene and the brightness of the holographic light pattern appearing at each
18 bright point of light while minimizing undesired diffracted light patterns.

19 SUMMARY OF THE INVENTION

20 It is an object of the present invention to provide a far field hologram viewing
21 device.

22 It is another object of the present invention to provide a method of manufacturing a
23 far field hologram.

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1 It is yet another object of the present invention to provide a far field hologram
2 viewing device through which a scene may be viewed by an observer in combination with
3 holographic diffracted light patterns at each bright point source of light present in the
4 scene.

5 It is still another object of the present invention to provide a far field hologram
6 viewing device which produces a desired reconstruction pattern that is not accompanied
7 by a copy of the pattern that is rotated by 180 degrees about an un-diffracted component.

8 It is an object of the invention to provide a robust approach to controlling
9 diffraction efficiency of far field holograms in order to achieve a balance between the
10 clarity of the scene and the brightness of the holographic light pattern appearing due to
11 each bright point of light while controlling undesired diffracted light patterns.

12 It is another object of the invention to control the diffraction efficiency for
13 multilevel phase computer generated holograms that are not limited to producing
14 symmetrical holographic light patterns, and therefore allow for larger and more detailed
15 diffracted light patterns than are possible with amplitude holograms and binary phase
16 holograms.

17 It is yet another object of the invention to establish a procedure that is consistent
18 with established cost-effective hologram fabrication processes.

19 It is a further object of the invention to provide the balance between the clarity of
20 the scene and the brightness of the holographic light patterns without requiring a tight
21 tolerance on the relative positions of the hologram and an observer's eye.

22 The present invention includes far field viewing devices employing novel reduced
23 diffraction efficiency far field holograms having regions of spatially varying diffraction

1 efficiency. The method also includes the step of substituting a low diffraction efficiency
2 pattern for at least one selected region of the far field hologram.

3 Some of the above objects are also obtained by a filter for use with a camera that
4 has a light gathering path and an image sensor. The filter includes a far field transmission
5 hologram that has a graphic image encoded therein. The far field transmission hologram
6 is adapted for mounting in the light gathering path. When the far field transmission
7 hologram is mounted in the light gathering path, the graphic image is superimposed, with
8 substantially no reversed diffracted copy of the graphic image, on a natural scene as
9 viewed by the image sensor through the hologram. The superimposed graphic image and
10 the natural scene are viewable by the image sensor in combination with substantial clarity.

11 BRIEF DESCRIPTION OF THE DRAWINGS

12 Additional objects and advantages of the present invention will be apparent in the
13 following detailed description read in conjunction with the accompanying drawing figures.

14 Fig. 1 illustrates schematically a human observer looking through a far field
15 viewing device.

16 Fig. 2 illustrates a view for an observer of a scene while looking through an ideal
17 far field viewing device.

18 Fig. 3 illustrates a view for an observer of a scene while looking through a high
19 diffraction efficiency far field hologram.

20 Fig. 4 illustrates a view for an observer of a scene while looking through a
21 conventional multilevel phase CGH.

22 Fig. 5 illustrates an SVDEFF hologram.

23 Fig. 6 illustrates a diffraction pattern produced by a square aperture.

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1 Fig. 7 illustrates a diffraction pattern produced by a multilevel phase FFMFF
2 hologram with small square low-diffraction regions.

3 Fig. 8 illustrates a view for an observer looking through a far field viewing device
4 employing FFMFF hologram with excessively large low diffracting regions.

5 Fig. 9 illustrates a view of an FFMFF hologram according to a preferred
6 embodiment of the present invention.

7 Fig. 10 illustrates a controlled diffraction efficiency far field viewing device
8 wherein FFMFF holograms are incorporated into the lens apertures of a spectacle frame
9 according to a preferred embodiment of the present invention.

10 DETAILED DESCRIPTION OF THE INVENTION

11 A standard far field hologram is typically optimized to create maximum brightness
12 holographic light patterns and consists of highly diffracting regions over the face of the
13 entire hologram. According to the present invention, a far field viewing device includes a
14 hologram with a diffraction efficiency chosen to balance the clarity of the scene with the
15 brightness of the holographic light reconstructions.

16 The desired clarity of the scene is such that the natural scene can be appreciated
17 without undue effort. In other words, it is desired that the observer still be able discern the
18 aesthetic qualities of the natural scene while looking through the far field transmission
19 hologram. Good tests for scene clarity (since aesthetic discernment is too cumbersome to
20 evaluate) assess how well an observer can read while looking through the holograms. A
21 near-reading test is to determine whether the observer looking through the holograms can
22 still read text of a standard publishing font size at what would ordinarily be a comfortable
23 reading distance for that person. A far-reading test is to determine whether the observer
24 looking through the holograms can make out street signs and road signs without undue

1 effort. Alternately, standard comparative visual acuity tests would be useful in evaluating
2 whether vision of scenery through the far field transmission holograms is substantially
3 clear if it meets an objective standard, e.g., a "20/40" standard.

4 According to one embodiment of the present invention, the local diffraction
5 efficiency of the far field hologram is modified in a systematic way. Far field holograms
6 intended for far field viewing applications are typically designed to exhibit shift-
7 invariance. This means that as the far field hologram is translated laterally with respect to
8 an illuminating beam of light, the intensity distribution of the diffracted light pattern does
9 not change substantially. This also means that the entire hologram need not be illuminated
10 to produce the desired diffracted pattern. In practice, illuminating a very small portion of
11 the hologram will still reproduce the entire diffracted pattern. Note that if the portion is
12 made too small, the quality of the diffracted light pattern will degrade excessively. We
13 define a unit hologram region as the smallest portion of the overall hologram that produces
14 an acceptable quality diffracted pattern. Preferably, far field holograms used for far field
15 viewing applications are composed of spatially repeated copies of a unit hologram.

16 Similarly, for a fixed position hologram, the eye can make small rapid movements
17 without changing the diffracted light pattern. This shift-invariant property is generally
18 desirable so that the viewer does not need to maintain a rigidly fixed position with respect
19 to the hologram.

20 In the case of a far field hologram illuminated by a beam of light, shift-invariance
21 means that as the far field hologram is translated laterally with respect to an illuminating
22 beam of light, the intensity distribution of the diffracted light pattern does not change
23 substantially.

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1 diffracting regions 530 are important design parameters that affect the usefulness of the
2 resultant holograms in the context of a far field viewing device.

3 When the size, shape and distribution of the low diffracting regions 530 are chosen
4 appropriately, the primary effect is to lower the brightness of the holographic light patterns
5 while simultaneously increasing the scene clarity. Control over the percentage fill of the
6 diffracting region of the hologram over the utilized hologram area 18 controls the effective
7 diffraction efficiency of the hologram and adjusts the balance between holographic light
8 pattern brightness and the scene clarity. Increasing the fill factor increases the effective
9 diffraction efficiency and tends to brighten the diffracted light patterns at the expense of
10 scene clarity. Decreasing the fill factor decreases the effective diffraction efficiency and
11 tends to increase scene clarity at the expense of reducing the brightness of the diffracted
12 light patterns.

13 In addition to the primary effect of increasing scene clarity, the addition of low
14 diffracting regions 530 creates a secondary effect of introducing undesired diffracted light
15 patterns that distract from the desired holographic reconstructions. This can be understood
16 by considering diffraction by a mask that is clear in the regions corresponding to the low
17 diffracting regions 530 of an FFMFF hologram and opaque in the regions corresponding to
18 the high diffracting regions 528. Such a mask will produce a unique far field diffraction
19 pattern corresponding to the shape of low diffracting regions 530. This same diffraction
20 pattern will be produced by the corresponding FFMFF hologram and in many cases will
21 distract from the desired holographic reconstruction. In the example of Fig. 5, the low
22 diffraction efficiency regions 530 are regularly spaced square regions.

1 Referring to Fig. 6, a far field diffraction pattern is illustrated. A clear square
2 aperture produces a far field diffraction pattern and consists of a main central spot 632 and
3 multiple diffracted spots 634.

4 Referring to Fig. 7, a view of a single compact point of light as seen through an
5 FFMFF hologram with square low diffracting regions with inappropriate sizes is
6 illustrated. An undesired diffracted pattern corresponding to the square low diffracting
7 regions is shown consisting of a main central spot 732 and unwanted diffracted spots 734
8 as well as a desired diffracted light pattern 722 produced by high diffraction efficiency
9 regions. The lack of an unwanted mirror image of the desired diffracted pattern implies
10 that the high diffracting regions are in the form of a multilevel phase CGH. The unwanted
11 diffracted spots 734 can be very bright in practice and distract from the appearance of
12 desired diffracted pattern 722.

13 One solution to the problem of the distracting undesired diffracted pattern is to
14 reduce the size of the square low diffracting regions in order to increase the spacing
15 between the undesired diffracted spots so that the first unwanted diffracted spot is out
16 beyond the extent of desired diffracted light pattern 722. In the specific case of the grid of
17 square low diffracting regions, the designer would then decrease the size of the individual
18 squares while attempting to maintain the same overall percentage fill factor by
19 appropriately reducing the spacing between regions. The choice of very small regions can
20 push unwanted diffracted spots 734 further out beyond the extent of the desired diffracted
21 light pattern 722. However, the central spot 732 of the undesired diffraction pattern
22 broadens and corresponds to serious degradation in see-through performance and is
23 manifested as considerable blurring of the scene.

1 We prefer to make the low diffracting regions 530 as large as possible. The effect
2 of sufficiently large low diffracting regions 530 is to make the overall undesired
3 diffraction pattern small with respect to the desired diffracted light pattern 722 thus
4 minimizing the distraction. Simultaneously, the central spot 732 of the undesired
5 diffraction pattern narrows and this results in practice in improved see-through
6 performance leading to a sharper focus of scene elements.

7 Although we prefer making low diffracting regions as large as possible, the size
8 cannot be increased without limit. The upper limit on the size is illustrated, referring to
9 Fig. 8, where a large low diffraction region size relative to the utilized hologram area 818
10 has been chosen and the spacing has been chosen to preserve a fifty percent fill factor.
11 The utilized hologram area 818 is determined by a number of factors including the size of
12 the pupil of the eye 814 and the distance between the eye and the far field viewing device
13 (a hologram 810 mounted in a frame 812). When the hologram 810 is situated within a
14 few centimeters of the eye 814, the utilized hologram area 818 is relatively small and, as
15 shown in Fig. 8, the observer looks only through a low diffracting region 830 when one of
16 the apertures is co-centered with the center of the pupil of the eye. In that case, the
17 resultant effective fill factor over the utilized hologram area is zero and the observer will
18 see no holographic light reconstructions. The other extreme occurs when the hologram
19 810 is shifted laterally such that the field-of-view of the eye only permits highly
20 diffracting regions 828 of the hologram 810 to affect the view. In that case, the resultant
21 effective fill factor is 100 percent and the view of the scene elements will be blurred.
22 Other spatial shifts of the hologram 810 of Fig. 8 relative to the eye 814 will produce
23 different effective fill factors.

1 It is desirable to have an effective fill factor that is independent of the relative
2 position of the eye and the hologram. In order to achieve a position independent effective
3 fill factor, the size of the low diffracting regions and the repeat spacing should be chosen
4 such that several low diffracting regions are contained within each utilized hologram area.
5 According to the preferred embodiment, the number of low diffracting regions contained
6 in the utilized hologram area is in the range of about five or more.

7 In addition to choosing an effective size, the shape of the low diffracting regions
8 should also be selected to further decrease the distracting effect of undesired diffracted
9 light. It is desirable to use low diffracting region shapes that spread the diffracted energy
10 out over a larger area rather than producing concentrated spots of undesired diffracted
11 energy. As an example, circular low diffracting region shapes spread the undesired
12 diffracted energy into rings of light surrounding the main central spot that have lower
13 energy values per area than do the spots diffracted by comparable size square low
14 diffracting regions.

15 Referring to **Fig. 9**, a preferred embodiment of an FFMFF hologram **910** with
16 circularly shaped low diffracting regions **930** distributed across a region of high diffraction
17 efficiency **928** is illustrated. In this illustrated embodiment, over sixteen low diffracting
18 regions **930** fall inside a utilized hologram area **918**. Alternatively, the shapes of the low
19 diffracting regions may be carefully chosen such that any diffracted light would fall on
20 bright regions of the desired holographic reconstruction and hence create minimal
21 distraction.

22 Referring to **Fig. 10**, a preferred embodiment of a controlled diffraction efficiency
23 far field viewing device **1000** is illustrated, wherein FFMFF holograms **1010** are
24 incorporated into the lens apertures of a spectacle frame **1012**. Each of the FFMFF

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1 holograms 1010 has a distribution of both high diffraction efficiency regions 1028 and low
2 diffraction efficiency regions 1030. The combination of FFMFF holograms 1010 with
3 spectacle frames 1012 provides a viewing device 1000 that very naturally prompts a
4 person to don the device so that the holograms are juxtaposed with respect to the person's
5 eyes for easy viewing of the natural scene combined with the holographic images
6 produced by the holograms.

7 The distribution of the low diffracting regions 1030 is preferably tailored to
8 optimize the far field viewing device 1000. A regular grid of apertures produces a
9 sampling effect in the diffraction pattern that manifests itself as a fine grid structure
10 superimposed on the diffraction pattern. An irregular spacing of the apertures (as shown
11 in Fig. 10) reduces this sometimes distracting sampling effect.

12 A practical design example is given below to illustrate the design considerations
13 given above. Consider a computer generated multilevel phase far field hologram designed
14 to produce an asymmetric holographic reconstruction around each bright point of light
15 when incorporated into a far field viewing device. The device may be embodied in many
16 forms including an eyeglass worn or held close to the eye or a window mounted device.
17 In the case of the window mounted device the observer might stand as close to the window
18 as possible, so a choice of approximately two centimeters between the eye and the
19 hologram is appropriate for the cases of both the eyeglass and the window application.
20 Such a design approach for the window mounted hologram will also work when the
21 observer is far from the hologram. The choice of a small utilized hologram area is a
22 conservative one. In an application that precludes the observer from standing very close to
23 the window, larger low diffracting regions can be used.

1 For multilevel phase holograms produced with known fabrication methods, a fill
2 factor ranging from about 50 to 80 percent is preferred as producing a pleasing balance
3 between scene clarity and reconstruction brightness. Selection of a most preferred value
4 from within this general range depends on the ambient light level in the scene, the nature
5 of the holographic reconstruction and subjective interpretation of the viewers.

6 According to a working example, we use the particular goal of 75 percent fill
7 factor. According to our empirical data, for a screen placed two centimeters from the eye,
8 a typical human viewer looks through a utilized hologram area 18 having a size of about 1
9 cm in diameter. A reasonable design for SVDEFF holograms employs circular low
10 diffracting regions 30 having a diameter of 1 mm and a mean center-to-center spacing of
11 approximately 1.8 mm. A 1 cm diameter utilized hologram area will allow approximately
12 25 such low diffracting regions to contribute to the view of the scene. This configuration
13 produces an effective fill factor that remains close to 75 percent even when the hologram
14 is translated laterally with respect to the eye. The diameter of the circularly shaped low
15 diffracting regions proves to be sufficiently large to concentrate the undesired diffraction
16 pattern such that it creates minimal distraction from typical holographic reconstructions.

17 Physical fabrication of an SVDEFF CGH takes advantage of established CGH
18 fabrication methods without any need for nonstandard modifications. Instead, the
19 distribution of the low diffracting regions can be incorporated directly into the computer
20 generated hologram data prior to fabrication. In general, computer generated holograms
21 are produced by using numerical algorithms to calculate phase and amplitude
22 transmittance values that will result in a desired far field diffraction pattern.

23 Each value corresponds to the desired transmittance at a different spatial location
24 on the physical hologram. The resultant data set is used to drive any of a variety of

002260-092700 1 fabrication methods that impose the desired transmittance values onto a physical substrate.
2 In order to create the special case of an FFMFF CGH, a standard far field hologram
3 algorithm is initially employed to generate a data set to produce a standard shift-invariant
4 and highly efficient far field hologram. The designer then determines the necessary fill
5 factor to lower the effective diffraction efficiency by the desired amount. Then the size,
6 shape and distribution of the low diffracting regions are determined. Finally, data values
7 corresponding to the low diffraction regions of the FFMFF CGH are set to unity
8 transmittance with a constant relative phase. The modified data set is then used as the
9 input to a standard CGH physical fabrication procedure.

10 Optionally, in the event that the cost of manufacturing individual holograms in this
11 manner is excessive, the hologram is used as a master and copied or replicated using a
12 variety of techniques. As an alternative, a standard far field hologram is used as a master
13 and the replication procedure is modified to introduce the low diffracting regions at the
14 replication stage.

15 The above-described procedure permits a hologram producer to choose the size,
16 shape and distribution of the low diffracting regions according to the guidelines described.
17 However, the present invention is not limited to a production method that incorporates so
18 much human input. The present invention encompasses production procedures where an
19 automated algorithm incorporates the design of the size, shape and distribution of the low
20 diffracting regions into the calculation of the hologram. Such an automated approach
21 would also provide the improvements in the effectiveness of SVDEFF CGH's according to
22 the various embodiments of the present invention.

23 Similarly, a CGH designer can arrive at an SVDEFF hologram approximating an
24 FFMFF hologram in an indirect fashion without directly incorporating the low diffracting

regions into the hologram characteristics. Such an indirect method is achieved by specifying the overall hologram reconstruction as a combination of the desired diffracted pattern and a weak diffraction pattern such as might be expected from the circular low diffracting regions of an FFMFF hologram. A well implemented algorithm would ultimately converge to a subclass of an SVDEFF hologram having substantially low diffracting regions distributed throughout the otherwise high diffraction efficiency hologram. These indirectly designed holograms would differ from an FFMFF hologram in that the transitions from low diffraction efficiency regions to high diffraction efficiency regions would tend to be less sharp than the transitions of the simpler FFMFF special case.

There are numerous variations possible according to alternate embodiments of the basic embodiments described above. These various embodiments are grouped according to the aspect of the resultant device that they pertain to. This list is meant to be illustrative and not exhaustive. Furthermore, numerous combinations can be constructed by taking different variations from each of the aspects discussed below.

A first class of alternate embodiments is based on variations of the high diffraction regions of the hologram.

Although the above description emphasizes multilevel phase CGH's in the specification, the method also applies to binary and continuous amplitude CGH's, binary phase CGH's and all optically recorded far field holograms. Since the maximum diffraction efficiency obtained with each of these different processes of producing holograms is significantly different, the corresponding optimum fill-factors will also be significantly different.

According to an alternate embodiment, the high diffraction regions that contain the far field holograms for generating the desired light patterns are themselves spatially

1 varying. Thus, different high diffraction efficiency regions of the hologram could produce
2 different light patterns. Such a configuration, as a natural result, causes an observer to see
3 different light patterns in different parts of the scene.

4 Some alternate embodiments are based on various ways that the image generation
5 is conditioned upon the frequency of light of the light source impinging the hologram.
6 Multi-level phase far field holograms can be made to respond in a color selective manner
7 if the phase modulation is chosen correctly. For example, a multi-level far field hologram
8 that has been designed to work with red light will create a holographic image only when a
9 point-like light source of red color is viewed through it. For all other colors, the hologram
10 will not produce the encoded holographic image. Similarly the optical phase modulation
11 can be adjusted so that the hologram responds to blue or green light. A single far field
12 hologram can then contain regions that are tuned to lights of different colors in producing
13 different images. When a white light point source is viewed through such a hologram, it
14 will produce a multi-color image that is a superposition of individual images encoded in
15 far field holograms tuned to different colors. The technique for describing the design of a
16 color-selective far field hologram by adjusting optical phase modulation has been
17 described by Barton, Blair and Taghizadeh. See Ian M. Barton, Paul Blair, Mohammad R.
18 Taghizadeh "Dual-Wavelength Operation Diffractive Phase Elements for Pattern
19 Formation", OPTICS EXPRESS, vol. 1, no. 2 (July 1997) (published on the Internet).
20 Holograms incorporating these color selective effects are not inconsistent with the present
21 invention, and alternate embodiments of the present invention include appropriate phase
22 modulation to effect such color selective effects.

23 The present invention may also be optionally embodied using so-called "volume"
24 hologram construction. Holograms can be recorded in materials that are thicker than

1 several hundred micrometers. Such holograms have special properties and have been
2 discussed for display applications and optical storage applications for a number of years.
3 See J.W. Goodman, INTRODUCTION TO FOURIER OPTICS, McGraw Hill (2d ed. 1996).
4 Such holograms when reconstructed suppress the conjugate image. In addition, these
5 holograms can display color selective and angle selective behavior. This means that
6 volume holograms recorded with certain angle between the object and the reference wave
7 will reconstruct only when illuminated with a reconstruction wave impinging at an
8 appropriate angle. This property is utilized in a far field hologram viewing device
9 according to the present invention in the following way. Multiple holograms of different
10 images are recorded with reference beams coming at different angles. When this
11 composite hologram is used in viewing point sources located at different positions, the
12 holographic image reconstructed will depend on the location of the point source. This
13 leads to an enhanced viewing experience by generating several independently recorded
14 images to appear for light sources at different positions in the scene.

15 A second class of alternate embodiments is based on variations of the low
16 diffracting regions of the hologram.

17 The individual low diffraction regions need not all have the same shape and size.
18 Thus, according to one alternate embodiment, circles are mixed with polygons of varying
19 sizes in a single SVDEFF hologram.

20 Moreover, the shapes need not be restricted to simple geometric patterns. Thus,
21 another alternate embodiment employs a mix of low diffraction efficiency regions that are
22 shaped like various alphanumeric characters or graphic images. This results in an added
23 benefit of creating an esthetically pleasing appearance when viewed.

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1 Although the low diffracting regions are described above as being optically flat,
2 the low diffraction regions need not be perfectly optically flat in order to practice the
3 present invention. Fabrication limitations arising in mass production cause the low
4 diffraction regions to vary from being perfectly optically flat.

5 In addition to unintentional deviations from optical flatness, one alternate
6 embodiment calls for the low diffracting regions to have intentionally imposed phase
7 profiles in the form of weakly diffracting patterns. For example, the weakly diffracting
8 pattern is embodied as high frequency gratings that produce attractive light patterns
9 beyond the extent of the desired diffracted light pattern. Thus, the low diffraction
10 efficiency region can be utilized to augment and enhance the main light patterns without
11 introducing unacceptable loss in the see-through image quality of the scene.

12 According to yet another alternate embodiment, the low diffracting regions have a
13 phase profile produced by an indirectly computed SVDEFF.

14 According to a further alternate embodiment, the low diffracting regions have a
15 gradually varying amplitude transmittance as opposed to a uniform transmittance.

16 One way to embody the low diffracting regions of the present invention is to
17 intentionally introduce gaps between small unit holograms.

18 A third class of alternate embodiments is based on variations of the design and
19 construction of the far field viewing device.

20 The viewing device may be embodied as having two distinct eye openings, one for
21 each of a viewer's two eyes. In this case, the high diffraction portions of the respective
22 holograms for the left and right eye are optionally embodied as a stereo pair. The use of a
23 stereo pair generates a depth effect on the light pattern.

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1 It is permissible to embody the frame that holds the far field device that places a
2 hologram between the scene and the observer's eye in a variety of forms. The frame is
3 alternately embodied as eyeglass frames, jewelry, bookmarks, greeting cards, and frames
4 for mounting in (or on) windows.

5 According to another alternate embodiment, the far field device is incorporated
6 into an imaging system. Examples of imaging systems that will embody the present
7 invention are binoculars and telescopes. Use of far field devices according to the present
8 invention is not limited to any specific type of imaging system and may be incorporated
9 into any of a variety of possible configurations that interpose a far field hologram between
10 the observer's eye and the scene.

11 According to one embodiment, the far field device is incorporated in or near the
12 pupil plane of an imaging system that has a solid-state detector or film as the final
13 detection plane rather than a human eye. Some examples of such devices are film-based
14 still or movie cameras, as well as still or motion cameras utilizing solid-state type
15 detectors.

16 The far field holograms described above worked using transmitted light.
17 Holograms according to the present invention may also be embodied so as to work with
18 light reflected from them. An important consideration for designing such reflective far
19 field holograms is to account for the double optical pass through the hologram. According
20 to an exemplary embodiment, reflective far field holograms according to the present
21 invention are incorporated into stickers. When a sharp point-like light source is viewed
22 after being reflected by the far field hologram, the desired light pattern will appear
23 surrounding the light.

1 The present invention has been described in terms of preferred embodiments,
2 however, it will be appreciated that various modifications and improvements may be made
3 to the described embodiments without departing from the scope of the invention.

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